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Lubrication

A Technical Publication Devoted to the Selection and Use of Lubricants

THIS ISSUE

AVIATION FUEL VOLATILITY

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THE TEXAS COMPANY
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FOREWORD

Much has been written about knock ratings of aviation gasolines and their significance in regard to engine performance. Comparatively little information, however, has been published on volatility although admittedly it is at least as important, if not more so.

The data presented in this article is the result of years of laboratory research, engine tests and, more recently, flight tests, in all of which The Texas Company participated. Especially within the past few years much has been learned about volatility from flight testing in many types of engines under a wide range of climatic conditions.

This discussion on volatility contains data of value to engine builders, aircraft operators, and petroleum refiners alike. A clear understanding of volatility is vitally important to engine designers because of its effect upon distribution, power and cruising economy of their engines. Operators of long range aircraft are finding that a knowledge of fuel volatility is helpful in extending the range of their aircraft. The meaning of volatility is equally important to petroleum refiners as it guides their research towards discovery of better fuels, methods of increasing the supply, and lowering the cost. An ample supply of suitable fuel must not be overlooked, because it vitally affects the welfare of a nation in the event of a national emergency.

Developments in aviation fuels have been very rapid in the past few years largely because all three groups have worked in close cooperation with each other and realized the benefits of improved quality, simplification in the number of grades and standardized specifications.

The brief references to volatility of gas turbine fuels appearing in this article do not reflect the extent of work which is now underway. This field is being actively explored by the research organization of The Texas Company. For the most part, the discussion of volatility in this issue is confined to current types of spark ignition aircraft engines.

LUBRICATION

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AVIATION FUEL VOLATILITY

IT IS generally agreed that the two most important characteristics of fuels for reciprocating aircraft engines are anti-knock quality and volatility. Anti-knock properties and their importance have been the subject of a relatively great amount of discussion and review, both technical and popular, in recent years. Volatility, which is at least of coequal importance, has also been investigated, from both laboratory and operational angles. A report on the knowledge that has been gained, prefaced with a brief review of the basic theory of volatility, is presented in this article.

THE VOLATILITY of a substance has been defined as the relative tendency to evaporate, or vaporize. Evaporation represents a change from a liquid to a gaseous state, as demonstrated by the boiling of water over a fire or the evaporation of ethyl ether, the common anesthetic, when a can of it is opened. Substances such as ether and alcohol which evaporate rapidly under atmospheric conditions are considered volatile materials (or as possessing "high volatility"), whereas substances which evaporate very slowly unless subjected to extensive heating, such as heavy oils or tars, are considered non-volatile or as being possessed of "low volatility."

Thus volatility is only relative—it is possessed to lesser or greater degree by all matter. The components of air—oxygen, nitrogen and the rare gases—as well as other normally gaseous materials, are in reality "very highly volatile" substances. Elements and compounds which are normally heavy liquids or solids such as mercury, carbon, or iron, are conversely, extremely "non-volatile" substances.

The nature of volatility and the process of evaporation can best be understood by reviewing the molecular theory involved. Consider a liquid composed of a single compound, for instance. In this liquid, the molecules are in a constant state of motion, which motion is increased in velocity as temperature increases. Near the surface, individual molecules which are directed toward the surface are constantly moving past it, out into the space beyond. Some of them, acted upon by the restraining action of the large quantities of molecules around the surface, are forced back into the liquid, whereas others escape. Likewise, some of the molecules in the space above the surface are constantly passing back into the liquid. With these processes continuously taking place, at any given temperature with an enclosed space above an excess of liquid, a condition of equilibrium will be reached, so that the relative total amounts of liquid and vapor remain fixed.

At this condition, the vaporized molecules exert a pressure, equally in all directions, which is known as the "vapor pressure" of the substance at the particular temperature under consideration. This pressure is due directly to the kinetic energy of motion of the vaporized molecular particles, which motion in turn is dependent upon the temperature of the substance. Thus, the vapor pressure of a given compound is controlled by temperature. Figure 1 shows the effect of temperature on vapor pressure for iso-octane, a petroleum compound familiar to readers as the basis of the "octane" anti-knock scale.

For the condition at which the vapor pressure of a substance is equal to atmospheric pressure, the corresponding temperature is equal to the boiling point of the substance. (Fig. 1) At this temperature, or slightly above, the liquid changes rapidly into a vapor and with sufficient heat will evaporate entirely.* The additional heat required for vaporization is known as the Latent Heat of Evaporation and is usually expressed in BTU per pound. The size of this quantity varies for different substances but may be illustrated by the fact that the Latent

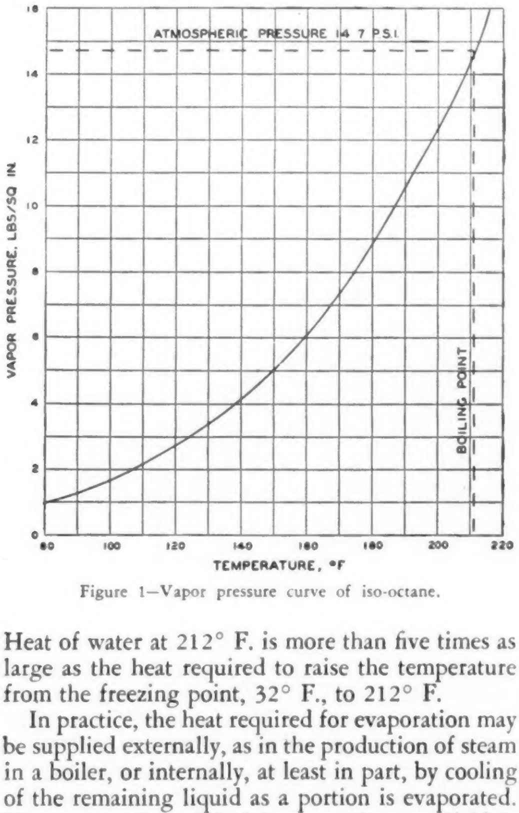


Figure 1—Vapor pressure curve of iso-octane.

Heat of water at 212° F. is more than five times as large as the heat required to raise the temperature from the freezing point, 32° F., to 212° F.

In practice, the heat required for evaporation may be supplied externally, as in the production of steam in a boiler, or internally, at least in part, by cooling of the remaining liquid as a portion is evaporated. The evaporation of fuel in an engine manifold is normally accomplished by a combination of these methods, using heat transferred from the engine parts and air. Further heat to complete vaporization is added near the inlet valve and in the combustion chamber.

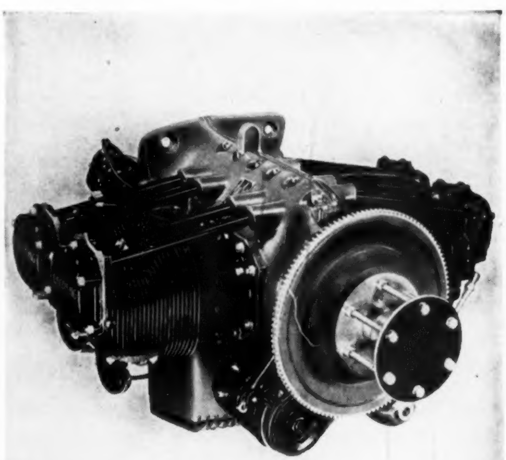
In the case of systems containing more than one compound, such as might be represented by liquid water in the presence of air, if the total pressure above a liquid surface is held constant at a value below the vapor pressure of the liquid at the ambient temperature, all of the liquid will evaporate. On the other hand, if the total pressure is maintained higher than equilibrium vapor pressure, only sufficient vapor will be formed to maintain the equilibrium pressure for that particular temperature. In this case, the vapor pressure is the "partial pressure" of the vapor, and is an additive component of the total pressure. In any given circumstances, the total pressure may be maintained by the atmosphere, for example, or by a vent in a fuel tank, or even by an aircraft engine supercharger, for the particular conditions under which evaporation is taking place.

The above is only a brief explanation of evaporation phenomena. A more detailed explanation of the subject and that of the evaporation of gasoline under various conditions is available in the literature.

VOLATILITY OF AVIATION FUELS

So far, we have considered principally the volatility or evaporation tendencies of liquids composed of a single compound. Aviation fuels, such as 100 Octane Aviation Gasoline, are composed of mixtures of many such single compounds, which are practically all of hydrocarbon nature. For each individual compound, the structure and arrangement of the carbon and hydrogen atoms within the molecule govern the chemical and physical properties, including volatility. In general, volatility, expressed as the boiling point, is inversely proportional to molecular weight; and vapor pressure vs. temperature relationships vary consistently with the number of carbon atoms for compounds of similar structure.

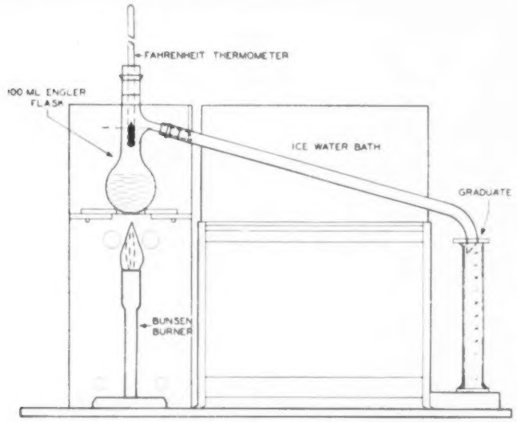
The volatility of aviation gasoline is governed by the volatility of each one of the many compounds



Courtesy Lycoming Division, The Aviation Corporation
Figure 2—The Lycoming Model 0-235-C four cylinder opposed aircraft engine rated 100 HP at 2600 RPM, sea level.

*The vapor-pressure temperature curve forms the basis of the well-known effect of altitude upon the boiling point of water. At sea level, the standard atmospheric pressure is 14.7 p.s.i. resulting in a boiling point of 212°F.; but at 10,000 feet, the standard pressure is only 10.1 p.s.i., and the corresponding boiling point from the vapor-pressure vs. temperature curve only 194°F.

present in direct ratio to the proportionate amount of each compound. Since, for special cases, the actual amount of any one compound present is usually very small, the resultant mixture boils over



A S T M APPARATUS FOR DISTILLATION TEST

Figure 3—The ASTM Distillation Test Apparatus (Method D86).

a wide range and net volatility is only slightly influenced by the individual compounds which are present.

Distillation Tests — ASTM

For gasoline type fuels, volatility is normally measured by the ASTM distillation test, (Fig. 3). In this test, 100 ml. of fuel are heated in a flask at standard rate. When the first drop falls from the condenser into the graduated receiver, the temperature of the vapor in the flask is recorded as the

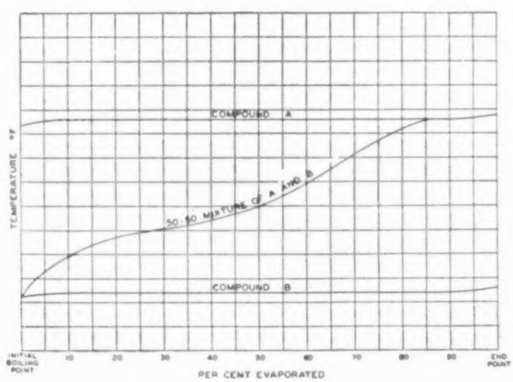


Figure 4—Representative ASTM Distillation curves for two pure hydrocarbons and for a 50-50 mixture of each.

initial boiling point (I.B.P.) for the fuel. The temperature is then noted and recorded for successive percentages of fuel condensed, which are 5%, 10%, 20%, 30%, etc., up to 95%. When the bottom of the flask has become dry, the thermometer reading is recorded as the end point (E.P.). Data so taken is plotted as temperature versus per cent distilled to indicate volatility graphically, (Fig. 4).

The distillation of nearly pure hydrocarbons results in practically a straight line on the ASTM distillation curve, A and B, Fig. 4. The distillation of a 50-50 mixture of these compounds results in a curve similar to that shown in the figure. Physically, this result is due to carry-over of some of the heavier compound upon initial boiling of the lighter, and retention of a fraction of the lighter compound in solution with the heavier material as the temperature is increased.

Aviation fuels, being a mixture of many such

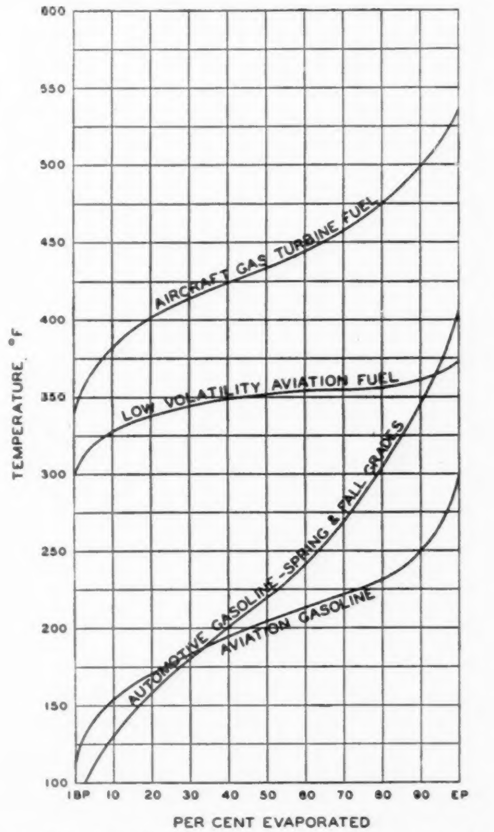


Figure 5—Typical ASTM Distillation characteristics for various types of fuels.

compounds, as previously noted, generally have smooth distillation curves extending over a wide temperature range. Typical curves for some common types of fuel are given in Figure 5, to illustrate the characteristics and boiling range of each. These are controlled by the purpose and conditions of use of the fuel, as will be discussed later.

Equilibrium-Air-Distillation

As will be appreciated, the conditions of evaporation of fuel in the ASTM distillation test differ widely from the conditions at which fuel is evapo-

rated in an engine manifold. This has led to the conception of Equilibrium-Air-Distillation,* which more nearly corresponds to engine evaporation conditions.

The apparatus for determining the EAD characteristics of gasoline is shown schematically in Figure 6. In this apparatus, measured quantities of fuel and air are mixed at a given temperature and pressure, after which the amount of fuel that has been vaporized can be determined from the quantity of liquid remaining. At any given mixture temperature, the amount of fuel evaporated, and therefore the vaporized mixture, is dependent upon the absolute pressure and upon the supplied fuel-air ratio.

The vaporization of gasoline in an Equilibrium-Air-Distillation Test and in an engine induction system differ principally only in the effects of external heat, pressure, time and turbulence. In an engine manifold and combustion chamber, the temperature and pressure vary considerably from the time fuel is first sprayed into the air until it is burned, and the heat required to vaporize the fuel is supplied from the air, manifold walls, and hot cylinder parts. In the EAD test apparatus, however, the temperature and pressure are maintained constant throughout evaporation and the required heat for vaporization is supplied externally. Similarly, sufficient time to establish equilibrium between the air, vapor, and liquid is allowed in the EAD method; while in the engine the required amount of time is not available. Thus the engine evaporation, at least until the mixture passes the intake valve, is inevitably less efficient than the Equilibrium-Air-Distillation, which may be considered the optimum condition obtainable.

*Equilibrium Volatility of Motor Fuels, O. C. Bridgeman, Journal Research — National Bureau of Standards, Vol. 13, July, 1934, p. 53.

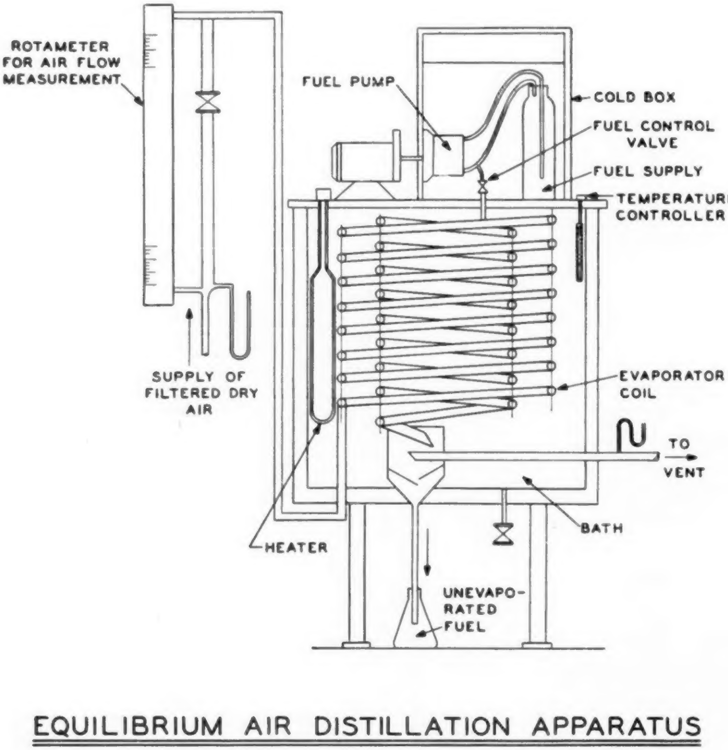


Figure 6—Schematic representation of the apparatus for determining Equilibrium Air Distillation data.

The EAD test is both complicated and expensive; therefore various methods of correlation have been established for determining EAD data from the more readily determined ASTM distillation of the fuel.* The accuracy of such correlations is satisfactory for practical purposes, so that the correlation method of calculating EAD data is commonly used. Alignment charts and graphical means have been devised to simplify the calculations, and are in general use in the petroleum industry.

Vapor Pressure — The Reid Vapor Pressure Test

In the petroleum industry, the vapor pressure of gasoline is measured by the Reid Method (ASTM D 323). The test is illustrated by Fig. 7. The bomb and the test sample are both prechilled, then the fuel chamber is filled and attached to the air chamber and gage assembly, which is submerged in a water bath at 100° F. for five minutes. After this interval, the bomb is removed from the bath, shaken, and resubmerged for another two minutes. The pressure is noted on the gage attached to the bomb, after which the process of removal, shaking, and resubmerging is continued until a constant pressure is obtained on the gage. Then, after correcting the gage pressure for the partial pressures of the air and water vapor, the resulting pressure is reported as the Reid Vapor Pressure at 100° F.

Except for pure compounds, or known mixtures of them, the Reid Vapor Pressure defines only one point on the vapor pressure-temperature curve and one point on the temperature-pressure-V/L curve. (At V/L = 4, since the volume of the liquid

*Bridgeman — op. cit.

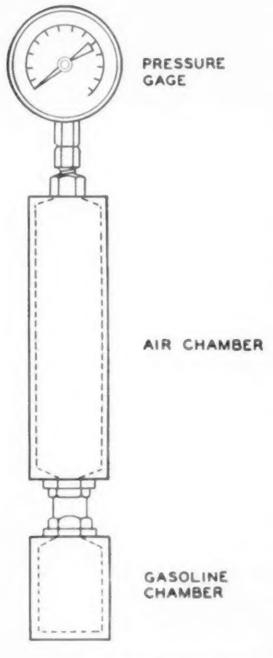


Figure 7—Test bomb used in Reid Vapor Pressure Test.

chamber is 1/5 that of the entire bomb.) In conjunction with the ASTM distillation temperatures for the 10% point and nearby sections of the distillation curve, however, it gives a valuable clue to both cold starting and vapor locking characteristics of aviation gasolines. Greater importance is now placed on the more fundamental properties described by the EAD and V/L characteristics of fuels, so that the RVP is used principally as an aid to manufacturing control.

Vapor-Liquid Ratio

Of major importance in the study of vapor forming characteristics of a fuel is the concept of vapor to liquid ratio (V/L) as a function of temperature and pressure. Such data may be obtained in the V/L apparatus shown in Fig. 8. The apparatus is essentially a calibrated burette, which may be charged with a measured sample and, by means of the surrounding liquid bath and a mercury leveling tube, subjected to various temperatures and pressure. V/L data may be read directly from the apparatus either at constant pressure or at various pressures, as desired. Through suitable calculations, basic vapor pressure versus temperature data may also be obtained. A third important use for the apparatus is found in studying the air solubility of gasolines, which is covered below.

Air Solubility

Gasoline, like water and other liquids, absorbs air in solution. The amount of air held in solution by gasoline at saturated conditions decreases as temperature increases and increases as pressure increases. This dissolved air is a major factor in vapor formation, and in certain cases can result in critical quantities of air and vapor being released in fuel lines and carburetors. This condition is further aggravated by the fact that the rate of air absorption or release is slight except under conditions of agitation. Thus fuel saturated with air at ground temperature and pressure may become supersaturated at the low pressures of high altitudes after rapid climb without appreciable cooling of the fuel. Subsequent agitation of the fuel in pumps, sharp bends, and other fuel system components results in release of large amounts of vapor.

The V/L apparatus is used in the study of the air solubility characteristics of gasolines by introducing a measured fuel sample to the apparatus and, after agitating to obtain equilibrium, determining the vapor volume reading at several different pressures at constant temperature. From data so obtained, the amount of air dissolved in the fuel may be calculated.

COMPONENTS OF AVIATION GASOLINE

It is of interest to examine the composition of typical aviation gasolines in order to determine just

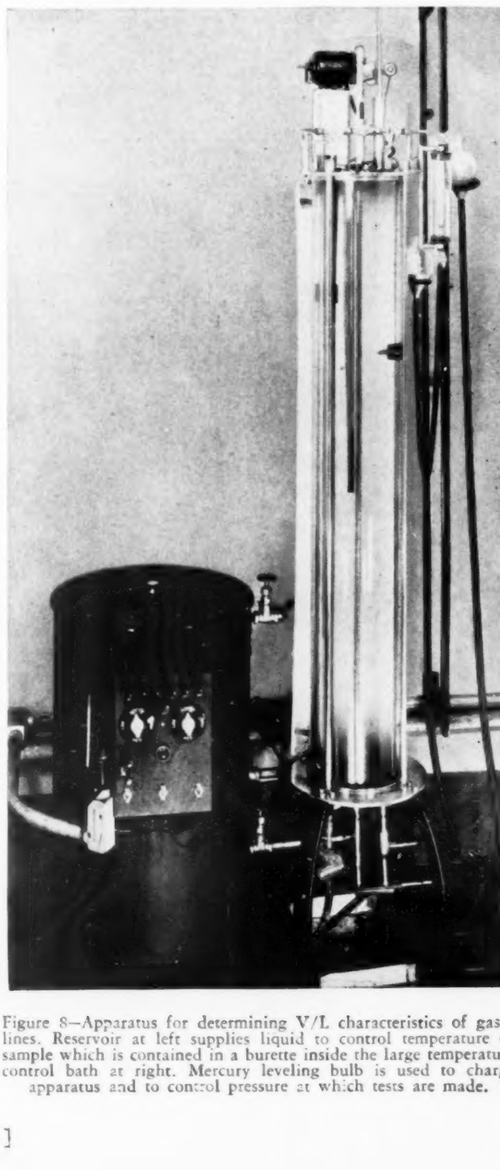


Figure 8—Apparatus for determining V/L characteristics of gasolines. Reservoir at left supplies liquid to control temperature of sample which is contained in a burette inside the large temperature control bath at right. Mercury leveling bulb is used to charge apparatus and to control pressure at which tests are made.

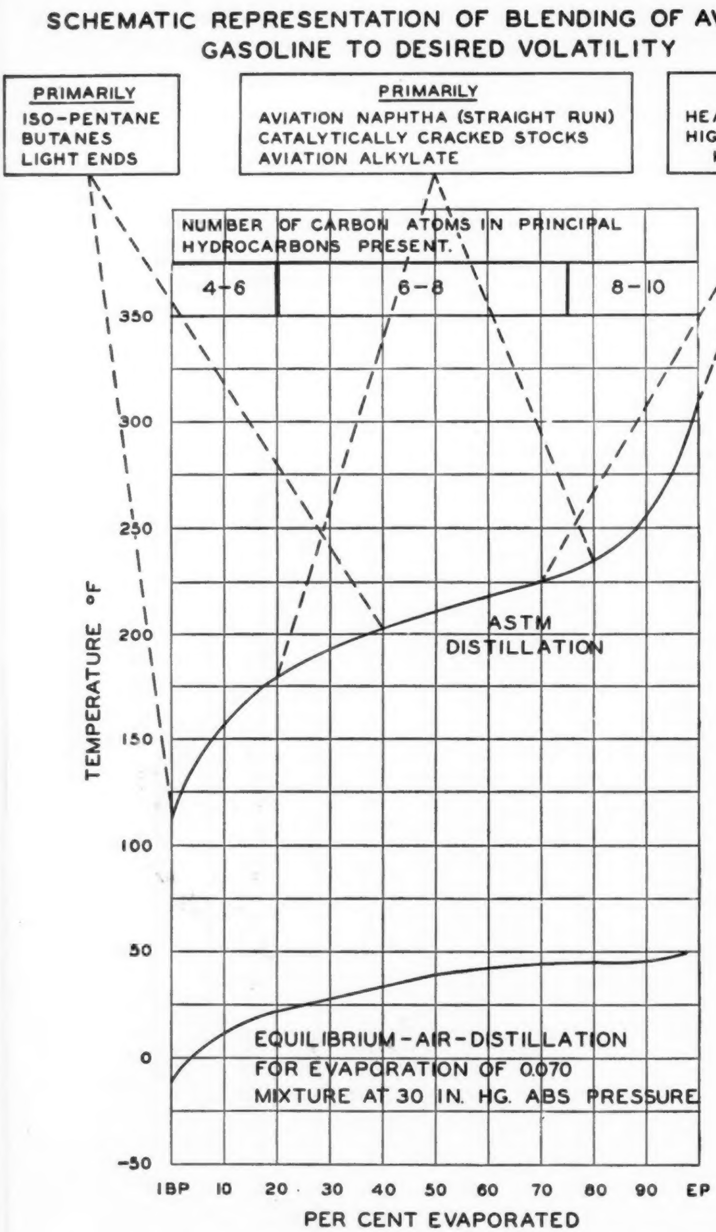


Figure 9—Schematic representation of aviation gasoline blending to control volatility, showing types of materials from which aviation gasolines are made and the resultant ASTM and Equilibrium Air Distillation curves.

how a given ASTM distillation is produced. This is illustrated graphically (with liberties) on Figure 9 for military and commercial aviation gasoline.

By blending against specification limits, a base stock consisting of aviation straight run gasoline or catalytically cracked product, or a mixture of both, is combined with high anti-knock material such as alkylate to achieve the desired anti-knock quality. The distillation of these components is controlled by the 50%, 90% and E.P. limitations on the final blend. Then, to obtain the desired initial volatility, very light material consisting of C_4-C_6 materials (4 to 6 carbon atoms) is added until the desired R.V.P. or maximum 10% point is reached. In high octane fuels, isopentane (with an unleaded octane number of approx. 91) has been used chiefly for this purpose.

The small amount of tetraethyl lead, or of other non-volatile fuel additives, being of the order of 0.1% by volume or less, ordinarily does not show up in the ASTM distillation.

Table I presents specification limits pertinent to volatility for five grades of aviation gasoline—two military and three civil. The adoption of specifications for civil aircraft fuels is not standardized on an over-all basis. The use of military specifications, however, is mandatory for military users and suppliers alike.

EFFECT OF VOLATILITY ON ENGINE OPERATION

The effect of fuel volatility on engine operation is very greatly influenced by engine design and operating conditions. Included among the operating conditions are atmospheric temperature and pressure, which are major factors in determining the behavior of fuels. Because of the influence of these factors, it is impossible to treat the subject of volatility without considering the engine and conditions involved. Certain problems or effects are more or less common to all aircraft engines, however, and may be discussed generally, with reference to specific cases where they apply. These are:

1. Engine Starting
2. Acceleration — Throttle Response
3. Vapor Lock
4. Fuel Losses from Vapor Formation
5. Cruise Economy
6. Maximum Engine Performance
7. Significance of Heavy Ends

Of these effects, the first four may be considered as under the control of that part of the fuel represented by the 5% to 50% portion of the ASTM distillation curve. Similarly, with the front end

TABLE I

Volatility Specification for Current Grades of Aviation Gasoline

	Military		*Most Limiting Civil Requirements*		
Grade	91/96	100/130	80	91/98	100/130
Reid Vapor Pressure, Max.	7.0	7.0	7.0	7.0	7.0
ASTM Distillation					
10% Evap., max. °F.	167	167	167	158	158
40% Evap., min. °F.	—	167	—	—	—
50% Evap., max. °F.	221	221	221	221	221
90% Evap., max. °F.	275	284	275	257	257
E.P.	356	356	356	338	338
Sum of 10% + 50%, °F. min.	307	307	307	307	307
Rec., %, min.	97.0	97.0	97.0	97.5	97.5
Res., %, max.	1.5	1.5	1.5	1.5	1.5
Loss, %, min.	1.5	1.5	1.5	1.0	1.0
Freezing Point, °F. max.	−76	−76	−76	−76	−76

fixed to control starting and vapor locking, the last three effects are influenced by the characteristics of the distillation curve above 50% evaporated. These distinctions also hold for the EAD curve, which, as we have seen, is closely related to the actual evaporation characteristics of fuels.

Many of the problems associated with fuel volatility have been under extensive investigation recently, both in the laboratory and in aircraft engines in flight. This work has been performed by the military air services, engine and aircraft manufacturers, airlines, and oil companies. Much of it was sponsored or directed by the Coordinating Research Council (CRC), a non-profit research organization comprised of representatives from the petroleum industry and from automotive and aviation manufacturers. The Aviation Fuels Division of the CRC Coordinating Fuel Research Committee has been especially active in providing information on fuel volatility.

A brief summary of the effect of volatility on the various phases of engine operation is presented below:

Starting

Before aircraft engines can be started under any conditions the differential expansion of engine parts and the oil viscosity must permit easy cranking and facilities for a strong spark must be provided. Techniques developed during the war, such as dilution of the lubricating oil with fuel to reduce the viscosity at low temperatures and the use of booster ignition coils, permit starting of unheated engines. Starting at low temperatures then becomes related to the volatility of the fuel, which is discussed below for different types of fuel.

Aviation Gasoline

Reciprocating aircraft engines of medium to high powers can be started on normal aviation gasolines at temperatures down to 0°F. to −10°F., dependent somewhat upon engine design and starting techniques.

Among the factors which affect ease of starting from the combustion process standpoint is valve overlap, which controls the amount of dilution of the incoming charge from residual gases left in the cylinder. Other factors are the air flow at cranking speeds and the means of supplying additional quantities of fuel to offset the effect of the small percentages that can be evaporated at low temperatures. This is customarily done by means of auxiliary primers, using nozzles located in the intake system, since the automotive type choke is banned for aircraft use.

For fuels of varying volatility, the Equilibrium Air Distillation characteristics afford a reasonably accurate measurement of starting properties. Detailed procedures for utilizing the EAD have been developed, yielding theoretical starting limits for given fuel priming rates. This is illustrated in Figure 10 for a hypothetical fuel under various starting conditions. With fixed priming rates, and fuels which are only partially evaporated at starting conditions, the limits for satisfactory operating at idling speed after starting do not coincide with the limits for possible starting mixtures. There is a fairly wide region of overlap between the lean limit under idling conditions and the rich limit under cranking conditions, however, and in this theoretical region starting and continued idling have been found practical. (Fig. 11.)

The effect of priming rate on time required for a start with a fuel of normal aviation distillation is shown in Fig. 12. Performance curves of this type have been found extremely useful in investigations of the proper volatility for starting of automotive

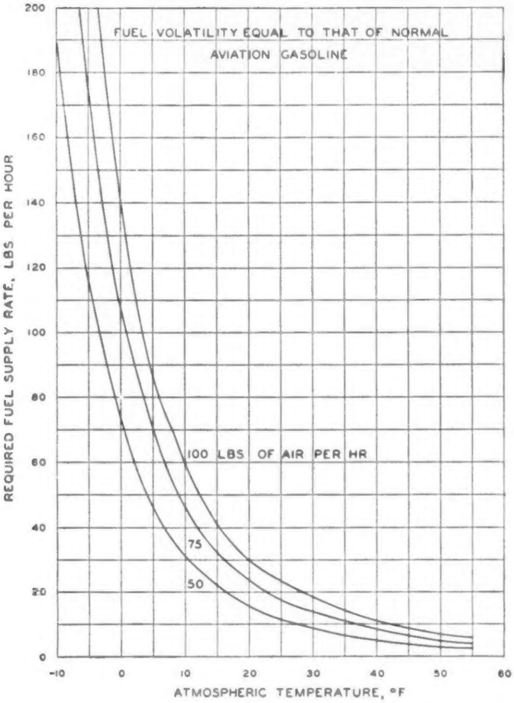


Figure 10—Fuel supply rate required for evaporation of 0.050 fuel-air ratio versus atmospheric temperature for assumed cranking air flow rates of 50, 75, and 100 lbs. of air per hour, using aviation gasoline of normal volatility characteristics.

engines, particularly when plotted back against ASTM distillation. The volatility considerations involved are largely applicable to aircraft engine starting, since design differences affect principally the cranking time scale absolute values, not the evaporation effects. Such a curve is given in Fig. 13, being a plot of the ASTM 10% evaporated temperature necessary to give a start in a fixed number of cranking revolutions versus atmospheric temperature. The four lines shown represent constant supplied mixtures of the values given.

Special Cold Starting Fuels

Since aviation gasolines ordinarily will not provide sufficient vapor to permit starting at temperatures below −10°F., special measures are necessary to ensure starting at very low temperatures. If sufficient time and equipment are available, ground heaters have been found effective in warming the entire engine, particularly the induction system, sufficiently to promote evaporation of starting mixtures. Such heaters supply large quantities of warm air, heated by burners which use motor or aviation gasoline.

Many military and commercial operations are not adaptable to the use of heaters, however; and, for them, the use of special cold starting fuels has been found effective. Such fuels consist of blends of light hydrocarbons with light aviation naphtha and other suitable components.

Starting fuels of two types have been used – the first type being very volatile, composed largely of petroleum gases, and having a high vapor pressure. Fuels of this type require special handling and metering equipment, and ordinarily cannot be used in the regular aircraft fuel system because of excessive vapor formation in lines and carburetors. An extreme example of this type of fuel is propane, which boils at −44°F. Attempts have been made to develop a propane starting system, using pressurized containers and metering equipment. The weight and complication of this additional equipment have largely prevented its widespread use and adoption.

The second type of cold starting fuel has volatility characteristics intermediate between those of the super-volatile fuels and aviation gasoline. It may be made of petroleum C_4 fractions and higher, with suitable light base stocks to give a balanced distillation to the finished fuel. Since extremely high antiknock quality is not essential at the low mixture temperatures and reduced manifold pressures of starting and idling, such fuels do not require lead. The light hydrocarbons that are used generally have

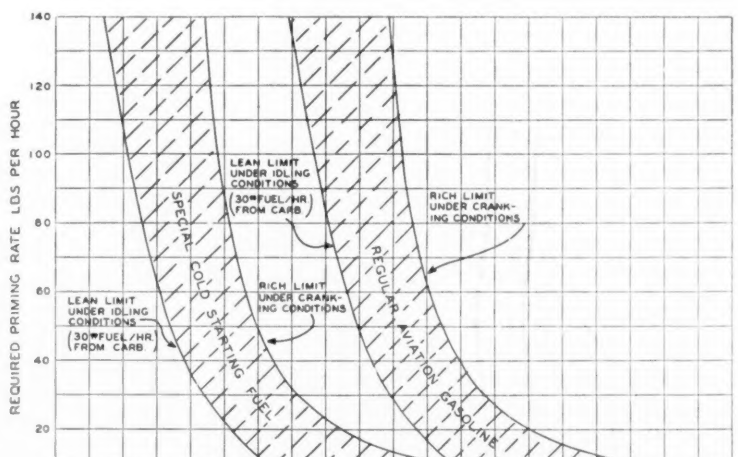


Figure 11—Priming requirements of regular aviation gasoline and of special cold starting fuel versus atmospheric temperature. Starting is possible within the shaded areas with each fuel, based on representative assumed cranking and idling air flows for 750 cu. in. aircraft engine.

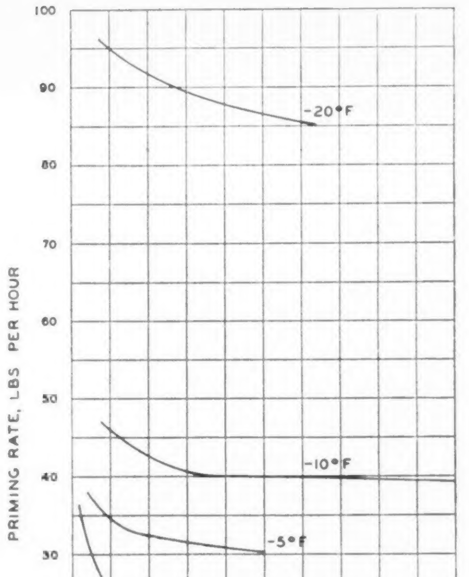


Figure 12—Effect of priming rate on starting time in medium size aircraft engine, using grade 100/130 aviation gasoline.

high anti-knock properties, adequate for the purpose.

The theoretical starting limits for such a fuel are shown at the left on Fig. 11. This fuel was designed to offer the same volatility at −65°F. as normal aviation gasolines provide at −10°F. Limiting the higher volatility features to this temperature provides a range of overlap with the normal fuel so that starting can be accomplished in a given engine over the entire atmospheric temperature range with only the two fuels and a simplified priming system. One advantage of such a fuel is that it also may be used in the engine carburetor for cranking and warm-up. When blended to the proper limits, this fuel will not vaporize in the carburetor and fuel lines to impede engine operation when starting at temperatures below +10° F. The vapor pressure is also such that the fuel may be shipped and handled in ordinary containers.

After the engine is started and warmed up sufficiently to run on aviation gasoline, which requires about two minutes at the lower starting temperatures, the fuel supply may be switched to the normal fuel lines, using solenoid valves or other suitable piping controls.

Low Volatility Fuels

With low volatility fuels of approximately 300-400° F. boiling range and 100°F. min. flash point, as proposed for air transport use, starting is difficult in current type engines. This would appear to require the use of auxiliary starting means such as cold starting fuels. To extend the usable range of such fuels as far as possible, it is anticipated that they may have characteristics like those of the cold starting fuels described above. Since low volatility fuels require direct cylinder injection, better starting may be possible through the further study of improved injectors for use with these fuels. Engine, and perhaps fuel, preheating is another possibility that may be developed.

In any event, starting problems with engines designed for the low volatility fuels are not insurmountable, and will be solved before the fuels are placed in service. Gas turbine engines of the turbo-jet type with anti-friction main bearings have been found relatively easy to start at low temperatures. As regards starting, at least, they may be considered relatively insensitive to volatility, since cold starts may be made with kerosene-type fuel.

Acceleration-Throttle Response

In automotive engines, acceleration characteristics have been found to depend upon the vaporized air-fuel mixture, independently of the particular fuel used. Equilibrium-Air Distillation data afford a means of determining the optimum evaporation characteristics of fuels. In practice, however, conditions may vary considerably from equilibrium, so that general relationships for fuel performance are lacking. Fuels with good starting characteristics and balanced distillation curves have been found to give satisfactory throttle response in aircraft engines. The situation is helped by acceleration devices built into aircraft carburetors, which supply additional fuel when the throttle is opened rapidly. The additional fuel aids in supplying an adequate mixture to all

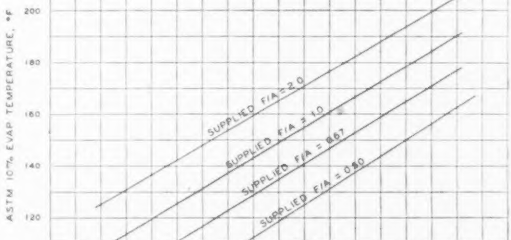


Figure 13—Maximum ASTM 10% point which permits starting within ten engine revolutions versus atmospheric temperature, for various supplied mixtures. (Based on data from automotive engine tests. Similar correlations would be expected for aircraft engines, with some displacement of temperature scales.)

cylinders. Not a minor factor in the picture, too, is pilot technique in operating the throttle which is important in increasing speed and power smoothly.

Vapor Lock

When air and/or fuel vapor interferes with the flow of fuel in the fuel system, the resulting condition is known as vapor lock.*

The result of this interference with fuel flow is a leaning of the mixture supplied to the engine, and in extreme cases, engine cut-out. Any leaning of the mixture from that desired for the operating conditions at hand is generally undesirable and often detrimental. At high powers such as are used for take-off and climb, leaning out increases cylinder head temperatures in air-cooled engines and also increases the tendency to knocking as a result of the leaner mixture and the higher temperature.** At the low powers used for cruising, leaning out from the already lean setting dictated by economy may cause roughness and intermittent cut-out. With fixed pitch or two position propellers, or with less stable constant speed and mixture controls, engine surging will result.

The tendency of fuels of different volatility to promote vapor lock is dependent upon their vapor forming characteristics. As we have seen, vapor forming characteristics are accurately defined in terms of V/L versus temperature. Thus temperature – V/L relationships provide a means of evaluating the effect of fuels upon vapor locking conditions.

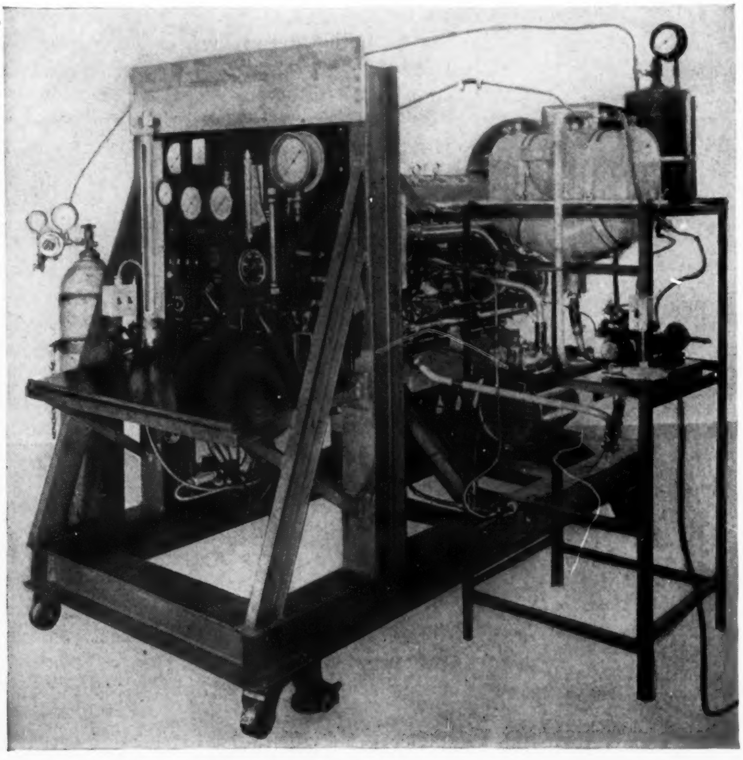


Figure 14—Laboratory test stand for cold starting tests with Ranger V-12 aircraft engine, with simulated fuel and oil systems on auxiliary test stand at right.

Effect of Dissolved Air

Vapor formation has been found to be seriously affected by the presence of dissolved air in the fuel.* Even though the amount of air involved is usually quite small, the effect of air release upon vapor formation may be large and may lead to vapor locking under conditions at which it ordinarily would not occur. As discussed previously, this effect is noted particularly when fuel which has been saturated with air on the ground is taken rapidly to high altitudes without evolution of the excess air. Under given circumstances, the evolution of vapor in a fuel system may be studied by analyzing the system and the V/L characteristics and air solubility conditions of the fuel.

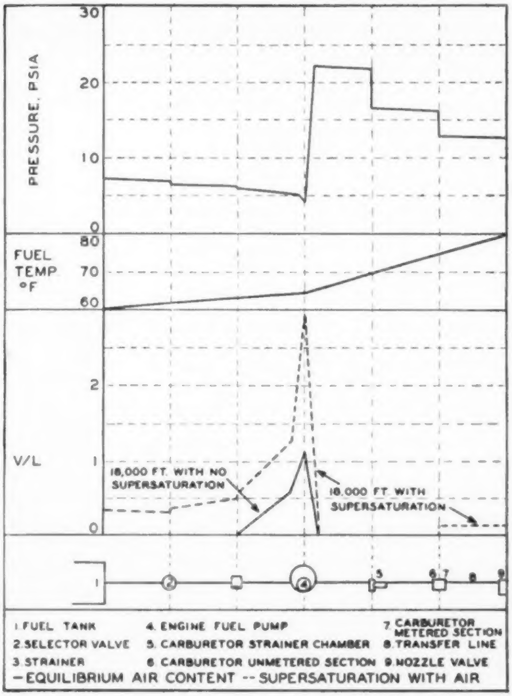
Results from such an analysis are given in Figure 15*, showing assumed conditions for 18,000 ft. altitude and V/L characteristics of an aviation gasoline with 7 psi RVP. The solid line on the V/L curve represents the vapor evolution when the gasoline was initially saturated with air at sea level and 60°F. and the air content reduced to equilibrium at 18,000 ft. by evolution of air within the tank during climb.

The dotted line on the V/L curve represents vapor formation in the fuel system at 18,000 ft. with no air evolution from initial saturation at sea level and 60°F. The fuel in the tank thus is supersaturated with air, which will be released, carrying large amounts of vapor along, upon agitation in the fuel system. Note the difference in V/L due to air content. If the pump is limited to a vapor capa-

*CRC Handbook – 1946, Coordinating Research Council, New York, p. 199

**Tendency to detonate varies with fuel-air ratio at constant cylinder head temperature, as well as decreasing with the lower head temperatures obtained by enrichening the mixture.

*Ibid, p. 287.



From CRC Handbook—1946
Courtesy Coordinating Research Council

Figure 15—Pressure—Temperature—V/L Diagram for simplified aircraft fuel system, showing effect of supersaturation with air.

city represented by a vapor liquid volume of 2, in the first case no difficulty will result. With supersaturation, though, the flow of fuel may be impeded at the pump, with resultant erratic engine operation.

Fuel System Analysis

The design and operating conditions of the fuel system, from and including tanks up to and including the point of discharge into the inlet air, control the performance of the system as regards vapor lock. As may readily be appreciated, temperatures vary throughout the system, usually increasing steadily from tank to discharge nozzle. Similarly, pressures vary from near atmospheric in tanks to a minimum value at the pump inlet; they reach a maximum at pump outlet, and decrease again up to the nozzle. An important factor in aircraft fuel system components is vapor handling capacity, since even though large amounts of vapor are formed, if they do not interfere with flow of liquid, engine operation may still be maintained. Many fuel system components are inherently limited in vapor handling capacity. For this reason, studies of temperature-V/L characteristics of fuels in relation to operating conditions of the fuel system are especially important in studies of vapor lock.

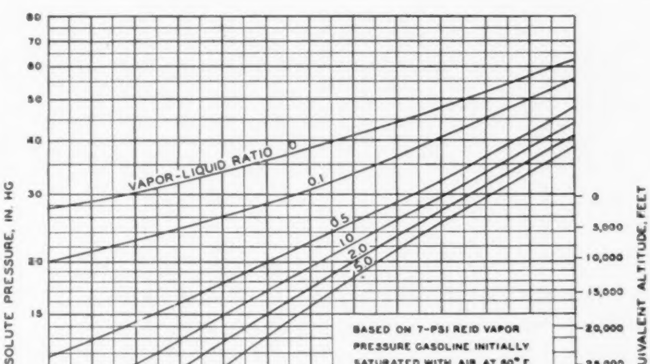
A plot illustrating vapor formation in an enclosed system for an aviation gasoline with 7.0 psi R.V.P. initially saturated with air at sea level and 60°F. is given in Fig. 16*. For other fuels, the vapor formation is dependent upon distillation characteristics and R.V.P. as well as upon initial air content. For a detailed treatment of this subject, the interested reader is referred to the 1946 CRC Handbook.

In general, aviation gasoline front-end volatility is the result of a compromise between the high volatility required for starting and throttle response and the practical limitations imposed by vapor locking and altitude losses. Satisfactory operation in both respects has resulted from distillation control and a R.V.P. limit of 7 psi. The vapor formed from such a fuel can be handled adequately with fuel systems of proper design, keeping in mind that pressures should be kept up and temperatures down as much as possible throughout the system. Strict attention to reduction of turbulence and pressure drop in piping, cavitation at pump inlets, and heating from pumps and hot engine parts, and the use of submerged booster pumps in the fuel tanks have alleviated vapor locking difficulties.

Vapor Losses

Vapor loss from fuel light ends is experienced principally either at high temperatures on the ground, as when fueled airplanes remain in the hot summer sun, or at altitudes, due to the effect of

*Ibid p. 242



From CRC Handbook—1946
Courtesy Coordinating Research Council

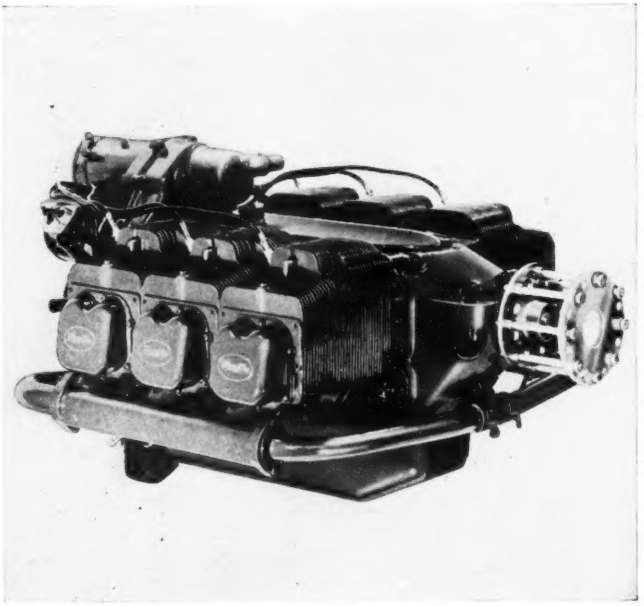
Figure 16—Vapor formation of an aviation gasoline.

reduced atmospheric pressure. These losses are in addition to those experienced in the fuel system from vapor which passes through the carburetor vapor vent. The latter is partially recovered through return lines back to the fuel tanks in larger aircraft; however, this provision usually is not made in fuel systems for personal type light planes.

Losses are worst of all when aircraft containing warm fuel climb rapidly to high altitudes without appreciable cooling of the fuel. Under these conditions, actual boiling of the fuel in the tanks can take place. In interceptors with a very high rate of climb and self-sealing fuel tanks (which may provide very effective insulation of the fuel, preventing cooling as the ship climbs), serious fuel losses have been observed. Losses in commercial service would not be as great but still might be high enough to affect over-all fuel consumption. Among the measures which have been found effective in reducing vapor losses is keeping the fuel cool prior to flight. Other remedies that have been suggested but never tested extensively, include:

1. Refrigeration of the fuel
2. Pressurization of the space above the tanks with nitrogen or CO_2 (which also might serve as a safety measure in military planes)
3. Recovery of the vapor through condensation systems.

The effects of vapor losses upon the anti-knock properties of the remaining portion of the fuel depend entirely upon the relative anti-knock qualities of the light ends and the heavier portions of the fuel. Thus high anti-knock aviation gasoline is usually increased in anti-knock quality by removal of the light ends, which results in a greater concentration of alkylate, aromatics, and T.E.L. as referred to the whole fuel. On the other hand, aviation gasolines for light planes and motor fuels will suffer slightly in octane value from loss of the light ends, which may have unleaded octane numbers as high as 90 to 95.



Courtesy Aircooled Motors, Inc.

Figure 17—150 HP Franklin "335" six cylinder air-cooled aircraft engine. Balance pipe connects two sides of inlet manifold for optimum torque characteristics in a given installation.

Cruise Economy

Apart from the loss of fuel (and consequently, dollars) through vapor losses, volatility exerts an effect on economy through utilization of fuel by the engine. Generally speaking, the utilization of fuel by a multi-cylinder aircraft engine having a carburetor metering system depends upon proper vaporization of the fuel after it is admitted to the intake air stream. Furthermore, good economy depends upon uniformity of the fuel-air mixture distributed to individual cylinders, which is related directly to vaporization in many engines. Obviously, it becomes increasingly difficult to supply a fuel-air mixture evenly to all cylinders if the fuel consists of a varying mixture of vapor and liquid.

The effect of volatility on economy has been found most severe at low mixture temperatures and leaner fuel-air ratios. These are obtained with various combinations of the following circumstances: low engine power and RPM and low atmospheric temperatures. Thus operation at low power for maximum cruising range at reduced temperatures has been found to be the most restrictive item with respect to fuel volatility.

Since front-end volatility is fixed for control of starting and vapor forming tendencies, only the portion of the distillation curve from approx. 50% evaporated upward can be changed to affect cruise economy, which is actually affected by the over-all distillation. Various attempts have been made to establish correlations of economy with ASTM or Equilibrium-Air distillation temperatures for single percentages evaporated such as the 80% or 90% points. It is now indicated, however, that the best indication may be obtained from the theoretical equilibrium percentage of fuel evaporated at the actual mixture conditions, as will be discussed later.

Large Commercial Engines

In larger commercial type aircraft engines, as carburetor air temperature is decreased, the best

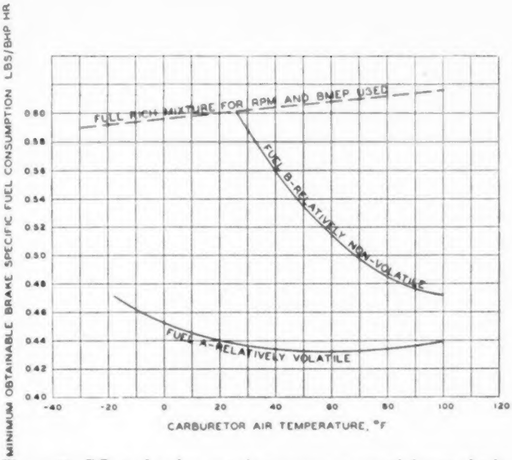


Figure 18—Effect of carburetor air temperature on minimum obtainable B.S.F.C. for two fuels with extremes in volatility characteristics. Hypothetical engine and fuels at assumed cruising power conditions.

obtainable brake specific fuel consumption is increased for a given fuel under fixed cruising procedure (constant power and engine RPM). This is illustrated by Fig. 18. The effect of carburetor air temperature is shown for two hypothetical fuels, one relatively volatile and the other relatively non-volatile as referred to aviation gasoline. Such a difference as that shown would never exist between fuels in service, as the differences in volatility represented are many times those found between the lightest and heaviest commercial aviation-grade gasolines. Note that, with some penalty in fuel consumption, operation may be extended to very low temperatures with the more volatile fuel; whereas, due to the limitation in enrichment at the power level used, operation with the heavier fuel is impossible below a relatively high air temperature. It should be pointed out that the operation typified by Fig. 18 represents a determination of the best obtainable brake specific fuel consumption for each air temperature, leaning out at constant power until best economy is obtained or else misfiring prevents further leaning, for the lower temperatures.

Using data from tests on many different fuels throughout a wide range in carburetor air temperatures, correlations such as that shown in Fig. 19 have been developed for specific engines at cruise conditions. While such correlations are limited as to practical use for operational purposes, they establish the dependence of engine performance upon the EAD characteristics of the fuel used and are valuable in research studies of volatility. Thus, the performance differences between various fuels are related directly to the Equilibrium-Air-Distillation of the fuels, which may then be used to predict their relative position with respect to cruise economy.

Other factors related to engine operation at cruising conditions have been found to depend upon fuel volatility. For example, in one engine model as carburetor air temperature was decreased, the temperature at which engine cut-out occurred with automatic lean mixture and fixed power was found to correlate with the 70% ASTM Distillation and EAD temperatures of the fuels used. In the same engine, the temperatures at which it was no longer possible to lean to best economy were found to depend, although less precisely, upon the 90% distillation temperatures of the fuels. In other types

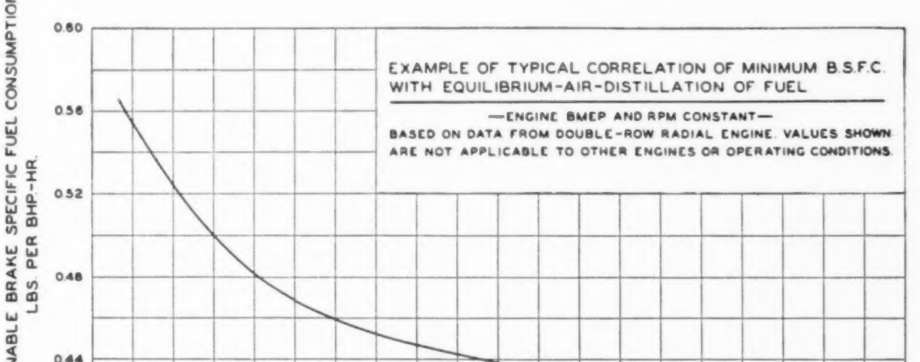
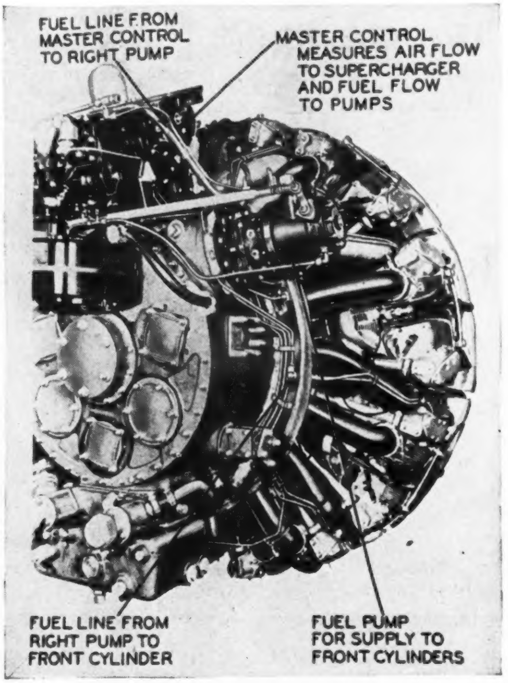


Figure 19—Example of typical correlation of minimum obtainable B.S.F.C. with Equilibrium Air Distillation of fuel. Curve shown is typical of that found with large radial engines under cruising power conditions, but is greatly influenced by engine design and operating conditions.

of engines, the temperature limits and same distillation percentages might not hold; however, there is sufficient data to indicate a reasonable dependence of performance upon fuel Equilibrium-Air-Distillation, with carburetor engines.



Courtesy Wright Aeronautical Corporation

Figure 20—¾ Rear view of Wright Cyclone 18 aircraft engine equipped with fuel injection, showing some details of injection system. This engine, which delivers as much as 2500 HP for take-off, is also available with carburetion fuel metering system.

The atmospheric temperature level which corresponds to a given EAD is affected by engine design, particularly mixture distribution characteristics and the relationship of mixture temperatures to atmospheric temperatures under cruising conditions. *There are large differences in current engine models in this respect, which differences sometimes serve to restrict production of aviation gasoline through limitation of fuel specifications to those for the most critical engines.*

Other Types of Engines

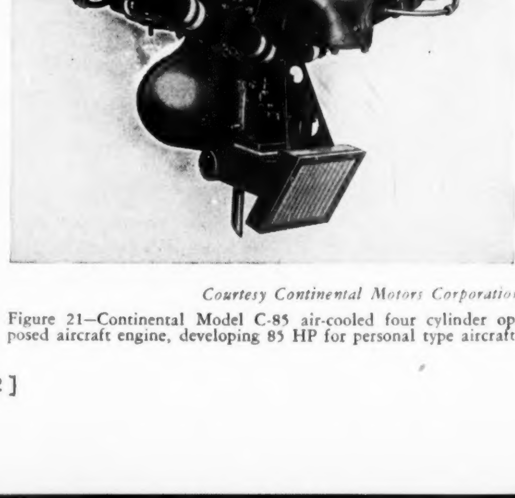
Fuel injection engines are able to utilize somewhat heavier fuels than are carburetor engines, although in them too, there is a limit to the minimum volatility that can be used without penalties in performance. Exact values for these limits have not been determined as yet; further developments are expected as the logical outcome of improvements in engine design. The fuel injection engine is, of course, well beyond the development stage; but most of the operation to date has been with conventional aviation gasolines, so that operation with less volatile fuels remains to be investigated thoroughly.

In engines for personal planes, the effect of volatility on cruise operation at low temperatures has not been a problem. This may be attributed in part to the fact that neither exceptionally low powers, mixture temperatures, nor fuel-air ratios are encountered. Other factors are heating of the mixture by exhaust muffs on the carburetor and the almost universal use of carburetor heat as a precaution against icing in winter or any sort of cold weather. Aviation grade gasolines for light planes have distillation characteristics making them sufficiently volatile to ensure satisfactory operation in flight under the most severe winter conditions.

Effect of Reduced Volatility on Detonation

An effect associated with volatility is a reported increased tendency to detonation at lean mixtures due to the incomplete evaporation of fuel at low carburetor air temperatures.* Unlike loss in economy due to lowered volatility, this effect is reported to be most pronounced at maximum cruising powers with automatic lean carburetor setting and low carburetor air temperatures. The effect has been explained by the theory that the mixture supplied to some cylinders is brought into the knocking range by mal-distribution due to incomplete evaporation and also by segregation of high anti-knock components of the fuel such as T.E.L. and high boiling aromatics. A full knowledge of the subject has not yet been obtained, however, and the problem is made more complex because of differences in the sensitivity of various fuels to the effect of mixture

*Aviation Fuels — "What the Airlines Want and Expect"— SAE Journal, G. K. Brower, Mar. 1946, p. 125.



Courtesy Continental Motors Corporation

Figure 21—Continental Model C-85 air-cooled four cylinder opposed aircraft engine, developing 85 HP for personal type aircraft.

temperature on knocking. Since the distillation range involved in the observed effect is higher than that of present commercial aviation fuels, the problem is causing no immediate difficulties. A revision of specification distillation temperatures upward might necessitate thorough study of such an effect and investigation of the part played by volatility, temperature sensitivity, and concentration of antiknock quality in the heaviest fuel components.

Engine Performance

Good mixture distribution and efficient combustion of fuel are essential in obtaining maximum engine performance. These factors are related to evaporation characteristics of the fuel in carbureted engines, inasmuch as almost complete vaporization is usually necessary to obtain either.

In supercharged engines, operation at high speeds and powers results in high mixture temperatures, which generally offsets any effect of lowered volatility when using heavier fuels. In some cases, using relatively non-volatile aviation gasolines (ASTM 90% temperatures well over 300°F.) slight losses in power and economy have been observed. This effect will vary from engine to engine, apparently as a result of carburetion characteristics, mixture distribution, the relation of inlet mixture temperature to outside air temperature, and the ability of the engine to "digest raw fuel" entering the combustion chamber.

Very rich mixtures, like very lean mixtures, also tend to increase the effect of volatility on engine operation. Using fuels with ASTM 90% points of 280°F. or higher, there have been reported instances of power loss, roughness, and smoking when operating at very rich mixtures. These results are open to question, since in other cases such effects have been found to be independent of fuel volatility. For example, in one series of tests at low carburetor air temperatures, engine roughness occurred above a maximum limiting fuel-air ratio with several fuels with a wide range in distillation temperatures. As carburetor air temperatures were increased, however, the mixture could be richened slightly without encountering roughness. The mixture temperatures resulting from low winter temperatures are sometimes low enough to prevent complete evaporation of even the most volatile aviation fuels prior to the combustion chamber. Such incomplete evaporation aggravates mixture distribution, and will be made worse yet by excessively rich mixtures; therefore, in very cold weather carburetor settings should be kept inside the rich flow limits. Also operation of density compensating aneroids should be checked to prevent supplying excessively rich mixtures to the engine.

As power output and engine RPM are decreased, lower mixture temperatures are obtained for the same outside air temperatures. This leads to a progressively larger effect of volatility as power is decreased. At decreased powers it is both possible and economical to operate at lean fuel-air ratios, which makes the operation even more sensitive to volatility. Using less volatile fuels, as fuel-air ratio is decreased, rough operation and back-firing are encountered leading to mis-firing and complete power loss if continued. Operation with two fuels having extremes in volatility characteristics within the gasoline range is shown in Fig. 22. Note the effect of the fuel on power, specific fuel consumption, and misfire fuel-air ratio shown in the tests, which were run at constant manifold pressure and RPM. Again, it should be noted that the effect of volatility shown is many times greater than that which might be caused by the variations in volatility of fuels supplied commercially. In experimental investigations of the type described, it is desirable to extend the range of the variable under investigation (in this case, fuel volatility) to explore thoroughly the effects of such changes.

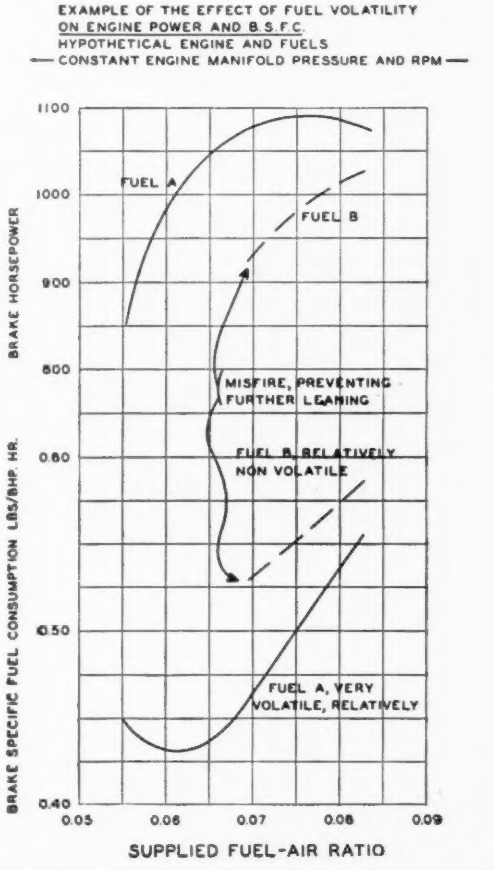
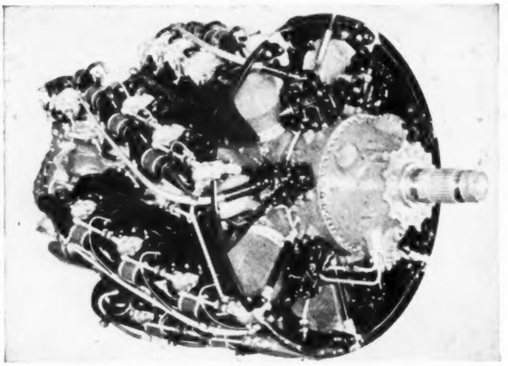


Figure 22—Example of the effect of fuels having extremes in volatility characteristics on engine horsepower and B.S.F.C. at constant manifold pressure and RPM.

The above discussion applies to high output commercial and military engines equipped with carburetors and constant-speed propellers. For engines with fuel injection directly into the cylinder, and for some types of gas turbines, the effect of volatility is less pronounced. Investigations are underway in both of these fields of development to determine optimum fuel characteristics.

Engines for light aircraft (below about 250 hp., arbitrarily) are not sensitive to small changes in the fuel ASTM 90% distillation region in the range of present aviation gasoline specifications. Since automotive fuels have ASTM 90% points as much as 100°F. or more above those of aviation gasolines, they are not recommended for light plane engines of current design, unless adequate information on fuel suitability is known.



Courtesy Pratt & Whitney Aircraft

Figure 23—The 28-cylinder Pratt and Whitney "Wasp Major" air-cooled engine, which develops more than 3650 combat horsepower.

Engine cutting out or failure to respond to the throttle after a long glide in cold weather has been suggested as a possible effect of volatility. The problem is largely obviated in light planes by the use of carburetor heat during glides in cold weather to prevent icing. No extensive investigation of the relation of volatility to cutting out in glide has been made. It may be deduced, however, that there would be an effect, with more volatile fuels giving less trouble; but that the most effective measures in dealing with such a problem would lie in equipment and procedure analysis.

Significance of Heavy Ends

The addition of high boiling materials to aviation fuels is sometimes advantageous for improvement of anti-knock quality and stability. If present in only small quantities, these substances do not affect the ASTM distillation curves, since the test is not sufficiently precise to reveal their presence. When added in appreciable quantities, as has been done with higher boiling aromatic hydrocarbons such as cumene, the ASTM distillation curve may be affected, even as far back as the 70-80% evaporated region. As we have seen, the distillation curve, particularly Equilibrium Air Distillation, for the 70-90% zone appears to govern cruising fuel economy and associated factors under conditions where the effect of volatility can be measured. Therefore, in any given case the effect of high boiling materials upon economy may be gauged from the effect upon the Equilibrium Air Distillation Curve.

The effect of heavy ends upon other phases of engine operation is less well defined, but has been investigated to some extent. Excessive oil dilution from fuel which passes the rings and increased cylinder wear have been reported from the use of fuels with ASTM 90% temperatures around 300°F. and higher. Other factors found to be affected by inclusion of heavier materials are an increase in induction system deposits and amplification of mixture distribution and stratification effects, especially when the heavy material is of high anti-knock value. All of these effects are dependent to a large extent upon engine design and operating conditions, as well as physical and chemical properties of the high boiling components involved, so that generalizations are difficult. Before such materials are used for any purpose, extensive laboratory and service tests are made to determine the effects on all phases of operation, so that fuels reaching service are satisfactory with respect to any heavy ends that may be present.

SUMMARY

In reciprocating aircraft engines with carburetor fuel metering systems, aviation gasolines of the volatility range represented by current supply give satisfactory performance with respect to starting, vapor lock, acceleration, economy, and maximum engine performance. The cooperative efforts of fuel suppliers and users and of engine designers have resulted in a well balanced matching of fuels to the engines in which they are used.

In the interests of petroleum conservation and national security, through ample supply of aviation gasoline in time of emergency, undue limitation to the ASTM 90% temperature are restrictive and undesirable. Such limitations serve to exclude many high anti-knock hydrocarbons. Utilization of fuels containing these materials is largely a matter of engine design, through inherently good mixture distribution and maintenance of mixture temperatures under cruising conditions. Engines can be designed to operate, without penalty, on fuels which do not restrict production nor waste valuable petroleum resources.

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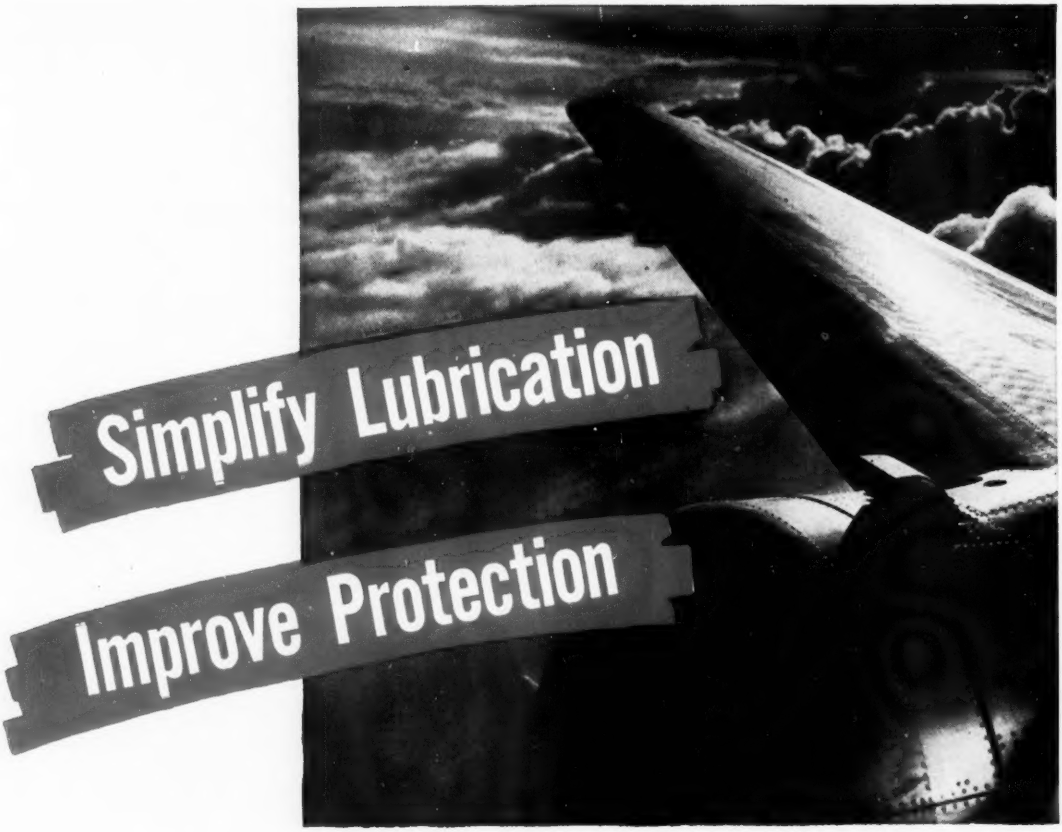

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